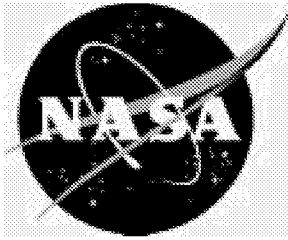# Simulation of an Impact Test of the All-Composite Lear Fan Aircraft

Alan E. Stockwell
Lockheed Martin Space Operations
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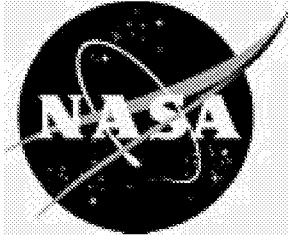
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Simulation of an Impact Test of the All-Composite Lear Fan Aircraft

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October 2002

Abstract

An MSC.Dytran model of an all-composite Lear Fan aircraft fuselage was developed to simulate an impact test conducted at the NASA Langley Research Center Impact Dynamics Research Facility (IDRF). The test was the second of two Lear Fan impact tests. The purpose of the second test was to evaluate the performance of retrofitted composite energy-absorbing floor beams. Since there were no structural drawings available to aid in the development of the model, a computerized photogrammetric survey was performed to provide airframe geometric coordinates. Over 5000 points were processed and imported into MSC.Patran via an IGES file. MSC.Patran was then used to develop the curves and surfaces and to mesh the finite element model. A model of the energy-absorbing floor beams was developed separately and then integrated into the Lear Fan model. Several measurements were required to account for structural details not included in the photogrammetric data, and limited testing was performed to verify material properties. Structural responses of components such as the wings were compared with experimental data or previously published analytical data wherever possible.

A symmetric half-model was generated to simplify analysis and model development. Comparisons with experimental results were used to guide structural model modifications to improve the simulation performance. This process was based largely on qualitative (video and still camera images and post-test inspections) rather than quantitative results due to the relatively few accelerometers attached to the structure. Observations were made concerning the importance of modeling fidelity for critical structural components, and suggestions were made for experimental and analytical process improvements.

Introduction

In cooperation with U.S. industry and the FAA, NASA is developing advanced structures technology for future aircraft that will be used for business and personal transportation. To support safety related issues, tests of composite structures are being conducted at NASA Langley Research Center (LaRC) to provide a database on the behavior of composite structures that have not necessarily been designed for energy absorption. These data would guide the development of concepts that improve vehicle crash response and behavior. Two full-scale Lear Fan composite test aircraft were recently tested at the NASA LaRC Impact Dynamics Research Facility (IDRF). One airplane was tested in essentially an "as is" condition to provide a baseline for an additional test with a modified subfloor structure that improves energy absorption.

A related goal of the crash research at LaRC is to advance the state of the art in the prediction of impact behavior during airplane crashes. MSC.Dytran is the primary simulation tool used to predict the dynamic response of aircraft during controlled impact tests at the IDRF. The present paper describes the modeling and simulation of the second Lear Fan test. Comparisons are made to test data, and various modeling techniques and analysis strategies are evaluated.

Problem Definition

Test Facility

A diagram of the LaRC IDRF is shown in Figure 1. The gantry structure is 240 feet high, 400 feet long, and 256 feet wide at the base. An 8-inch thick reinforced concrete impact surface is centered under the facility gantry and is approximately 396 feet long and 29 feet wide. The movable backboard is used for photographic clarity and camera referencing.
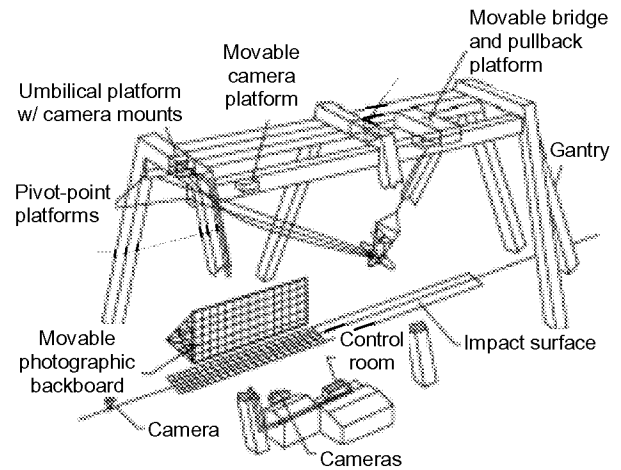

Figure 1. Diagram of Impact Dynamics Research Facility

The test vehicle is suspended from two swing cables, pulled back, and released to allow it to swing into the impact surface. Velocity and flight path angle at impact are controlled by adjusting the release height and cable lengths.

Instrumentation/Data Acquisition

Photographic data acquired for the Lear Fan test included high-speed video and lower-speed high-resolution video. Several cameras were positioned on the ground and on the gantry to record the Lear Fan test from three different views. Typical impact test camera placements are shown in Figure 1. In addition to the fixed cameras, several onboard video cameras were used to record the seat and passenger responses. Accelerometers were located at the seats and seat attachment points. The anthropomorphic test dummies were also instrumented to measure head, chest, and pelvis accelerations and lumbar loads. An onboard data acquisition system recorded the accelerometer and load cell output.
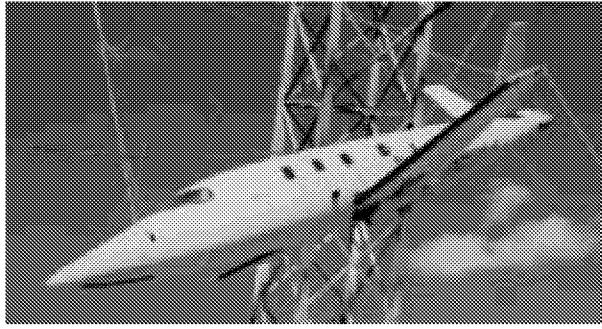
Test Specimen

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Figure 2. Lear Fan aircraft in pull-back position

The Lear Fan aircraft, shown in Figure 2, is a low-wing, twin-engine, pusher propeller general aviation airplane with a carbon fiber reinforced composite skin and frame construction. Both the wing span and the length of the aircraft are about 40 feet. The design gross takeoff weight is 7200 lbs, with a capacity for eight occupants. Details of the design and construction of the aircraft are given in Reference 1.

The fuselage used in the test was a non-flying ground-test structure. Avionics, seats, engines, propellers, tails, and landing gear were not included in the delivered aircraft. Dummy weights, simulated structure, and fuel tanks filled with water were used to match the weight and inertia of the actual aircraft. The fuselage was retrofitted with a composite energy absorbing floor and subfloor. The subfloor beams were based on a patented concept (Reference 2) designed to attenuate vertical impact forces. A detailed sketch of the design is shown in Figure 3. The final ballasted weight of the test vehicle was 7053 lbs. The seating layout, shown in Figure 4, was designed to accommodate various test objectives using a combination of forward-facing, side-facing, standard, and energy-absorbing seats. Also shown in Figure 4 are the locations of onboard accelerometers used to measure the structural response at the seat attachment points. The seat occupants, anthropomorphic test dummies, were instrumented with lumbar load cells and accelerometers in the head, chest, and pelvis.
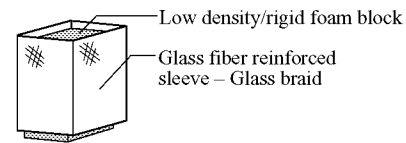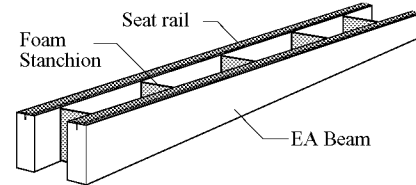

(a) Glass fiber is applied over foam blocks
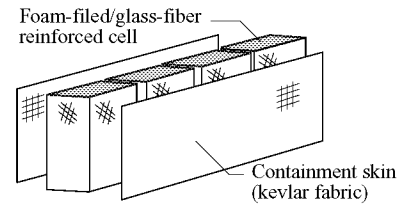
(b) Fiber reinforced foam blocks are assembled to form a panel or a beam
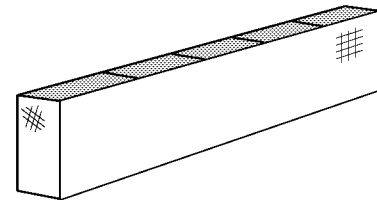
(c) Beam is infiltrated with resin, cured and cut to size.

(d) Beams are assembled in to a subfloor

Figure 3. Energy-absorbing subfloor beam

Test Impact Conditions

The aircraft struck the concrete at approximately zero degrees pitch relative to the impact surface. The yaw and roll angles were zero and –2.6 degrees respectively (i.e., the left wing hit slightly before the right wing). The vertical velocity was 31 ft/sec and the horizontal velocity was 82 ft/sec. A set of photographs illustrating the crash sequence is shown in Figure 5. The first two photographs show the airplane before impact, and the third photograph shows the airplane after the initial impact.

After the initial impact with the concrete, the aircraft continued to slide until it hit a plywood barrier that had been erected as a target for a
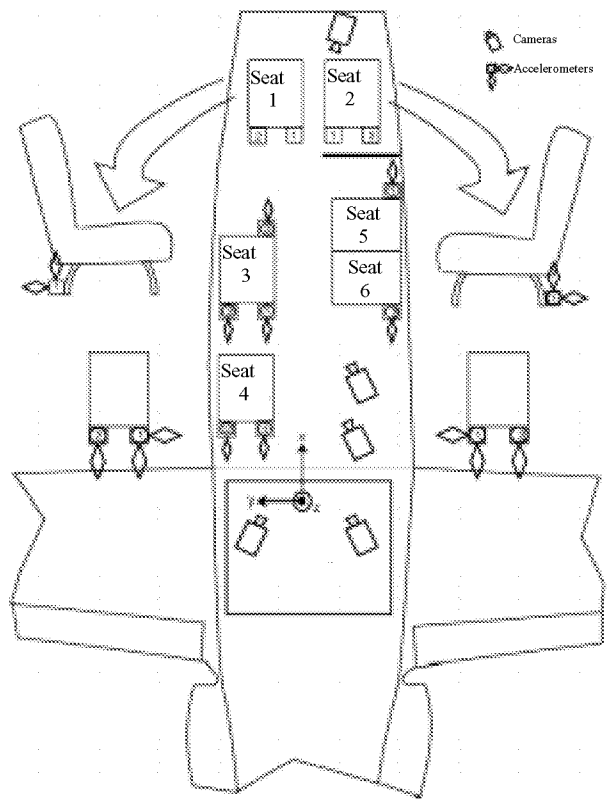
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Figure 4 Lear Fan seating and instrumentation

head-on impact. The purpose of this impact was to test the response of the side-facing seats. The head-on impact was outside the scope of the simulation, however it caused significant structural damage to the fuselage and interior structure. This complicated the task of post-test structural damage assessment.

Assessment of Structural Damage

Post-test inspections revealed damage to the fuselage that could be seen from both inside and outside the fuselage. In the bottom photograph of Figure 5, circumferential fuselage cracks can be seen. Inspection of the high-speed video showed that the cracks originated near the wing attachment points and progressed rapidly to the fuselage crown, effectively cutting the airplane in half.
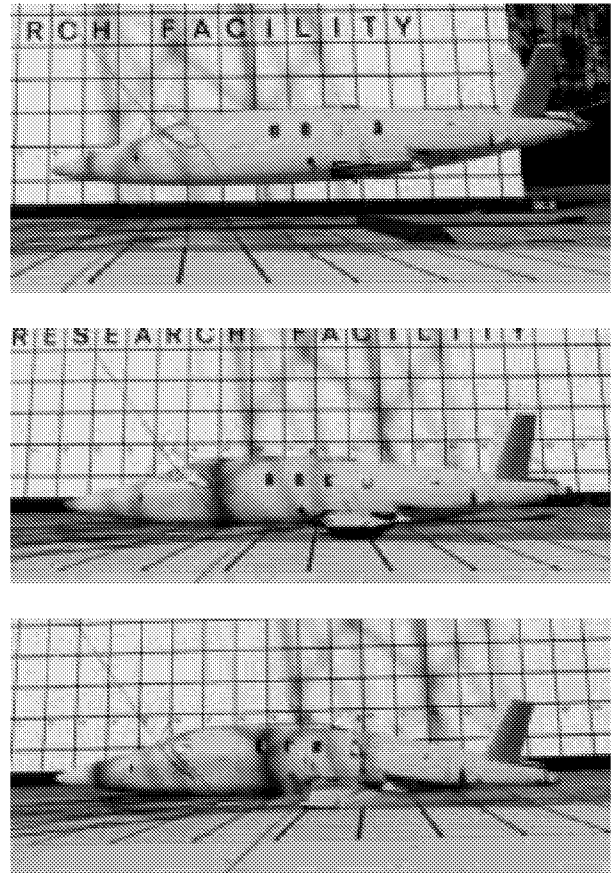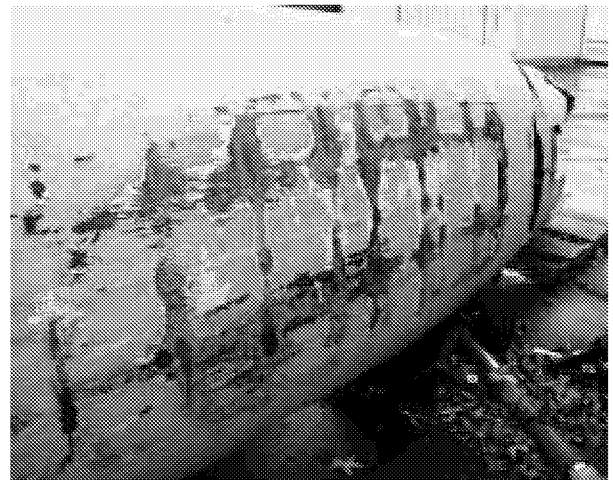

Figure 5. Crash sequence photographs

Figure 6. Exterior damage – underside of fuselage

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Figure 6 shows a view of the underside of the fuselage. The relatively symmetric pattern of the abrasion damage is further evidence of the near zero-degree roll condition. There is also no evidence of cracks or breakage in the fuselage skin.
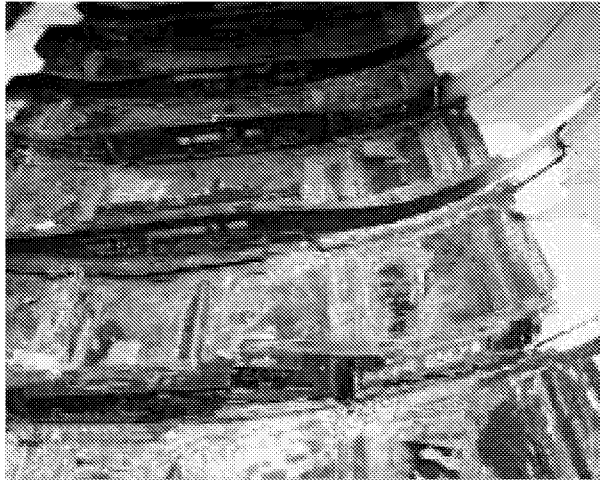

Figure 7. Interior damage – frame failure

Due to test instrumentation limitations, there was no video evidence of interior structural damage. Posttest inspections, however, revealed that several frames failed both at the centerline and outboard of the subfloor beams. This damage is shown in the photograph in Figure 7. Since the frame failure was similar to damage found in the first Lear Fan test, in which only a single impact was experienced (i.e., there was no second, head-on impact in the test of the first fuselage), it was concluded that the frames broke during the initial impact.

Accelerations

Peak accelerations at the seat attachment points varied from 130 g's to over 200 g's according to seat location. The plot of seat accelerations in Figure 8 illustrates this variation for two of the seats. The accelerations in this plot were filtered with a 200 Hz Butterworth filter. The pulse for Seat 1 appears to be slightly ahead of the pulse for Seat 2. The peak response of Seat 2 also is spread over a larger time period. These
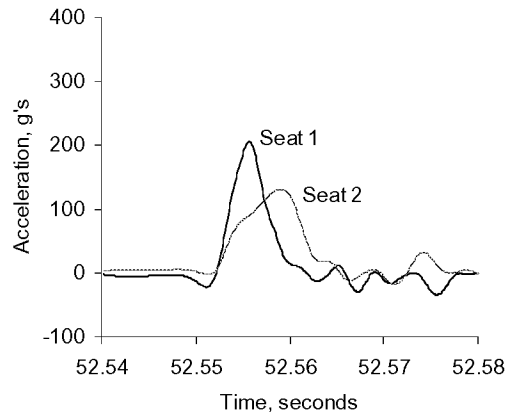

Figure 8. Vertical accelerations (g's) at rear inboard seat attachment locations

differences are due to the slight roll angle, which caused the left side (Seat 1) to hit first, and the difference in seat types, i.e., Seat 1 was a typical general aviation seat, and Seat 2 was an energy-absorbing seat.

Analysis

Simulation Objectives

The goal of the Lear Fan crash analysis was to demonstrate the feasibility of using simulation tools such as MSC.Patran and MSC.Dytran to predict the response of a complex aircraft structure to an impact, and to investigate modeling issues such as material characterization, mesh discretization, element types and the influence of modeling details.

Model Development

Structural drawings were not available to facilitate the creation of the finite element model. In order to obtain surface geometry a photogrammetric survey was conducted. The result of this computerized process was a set of

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International Graphics Exchange System (IGES) files containing over 5000 points, as shown in Figure 9. The IGES files were imported into an MSC.Patran database, and the points were
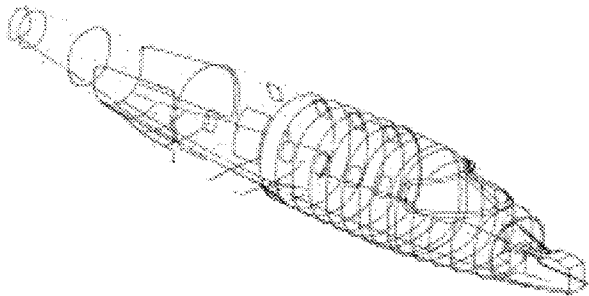

Figure 9. IGES file - points computed by photogrammetric survey

manually connected to form curves and then surfaces. This process proved to be tedious and time-consuming due to the large quantity of points, the inaccuracies inherent in the placement of the photogrammetric targets, and the difficulties in visualizing and editing complex 3-D geometry. After the surface geometry was defined, a combination of manual and automatic meshing was performed to generate the finite element model shown in Figure 10. Although the structure and interior seating layout were not exactly symmetric, a symmetric half-model was chosen for development purposes in order to reduce the model size, complexity, and run times.
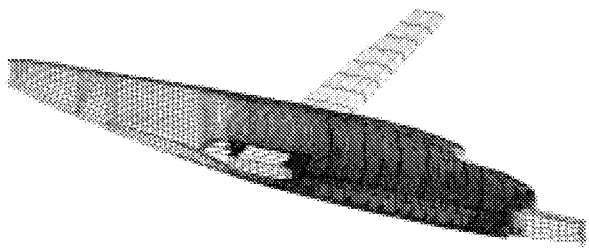

Figure 10. Finite element model – overview

Several visual surveys and hand measurements were required to model the frames, bulkheads, floors, wings, and features such as the simulated engine structure. The windows and doors were not modeled. Instead, it was assumed that the overall fuselage stiffness was not significantly affected by assuming a continuous structure. Several MSC.Nastran static analyses were conducted to verify this assumption. Limited dimensional information was obtained from original Lear design layout drawings and technical papers, and an ultrasonic thickness gage was used to map the fuselage skin thickness. This process was also time-consuming and tedious, and it proved to be impractical to apply the results directly to the finite element model. Instead, the thickness measurements were used to verify information obtained from technical papers and previous analyses, and to modify the baseline thickness in areas where the direct measurements were the only source of information.

Finite element meshes were created to model the fuselage and interior frames as shell elements. Some stiffeners in areas outside of the passenger compartment were modeled with beam elements. Lumped masses were used to model added mass, such as simulated engine masses, instrumentation and equipment.

Since wing modeling was not a major concern in terms of structural damage (post-test inspections revealed that the wing was not severely damaged), a simplified wing model was generated to obtain the proper mass distribution and to account for realistic dynamic structural interaction with the fuselage. The wing model was converted to MSC.Nastran format, and both static and normal-modes analyses were performed to verify the stiffness and mass properties. The results were checked against an equivalent beam model (also converted to MSC.Nastran) of the wing that had been developed in a Lear Fan study (Reference 3).

The energy absorbing subfloor beams were modeled separately (Reference 4) and then integrated into the MSC.Patran airplane model. This process also proved to be complicated due to the conflicting constraints on node spacing
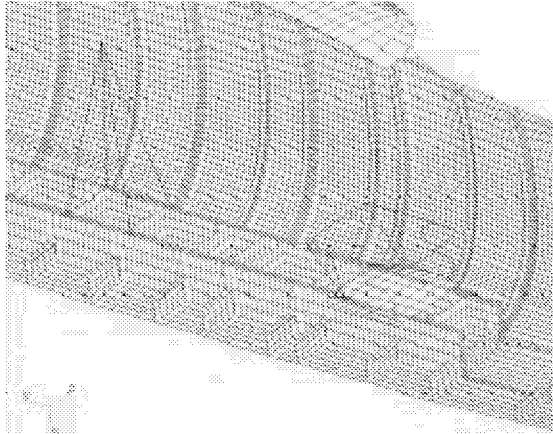

Figure 11. Passenger and subfloor beam modeling detail

dictated by the cellular design of the composite beams and the fixed location of the aircraft frames. A view of a typical subfloor/frame modeling detail is shown in Figure 11, and an expanded detail of a subfloor beam model is shown in Figure 12. The beam was subdivided into four elements in the primary load-carrying (vertical) direction in order to model the expected compressive response with a minimum number of elements. If the beams had exhibited more crushing during the test, the mesh would have required significantly more refinement.
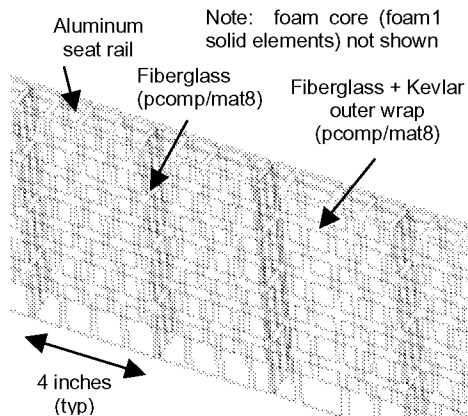

Figure 12. Subfloor beam modeling detail

The analysis was focused on the structural response of the aircraft. Therefore the dummies were not explicitly modeled or analyzed. Initial versions of the MSC.Dytran model did not include models of the aircraft seats either. Instead the combined seats and dummies were modeled as lumped masses tied to the subfloor beams by stiff beam elements. Seat models were introduced into later versions of the aircraft model to investigate possible solutions to the problem of excessive subfloor beam crushing.

Analysis Approach

Elements
The MSC.Dytran model was comprised of about 25000 elements, primarily CQUAD4 quadrilateral, single-integration-point, Key-Hoff shell elements. Beam elements were used to simplify modeling in non-critical locations, and solid elements were used to model the foam core of the subfloor beam cells. Element dimensions were limited to about $1 - 2$ inches in the refined fuselage region. This size was chosen to provide sufficient displacement and stress resolution while maintaining a time step of about one microsecond. For the symmetric half-model this resulted in run times of about 12 $- 15$ hours to simulate 0.020 seconds.

Materials
Simplified material models were used wherever possible. The quasi-isotropic layups of the fuselage skin and frames were modeled as isotropic elastic-plastic (DMATEP) materials with no strain hardening. Material properties were derived from tensile tests of coupons taken from the first and second Lear Fan fuselages. From this data, the elastic modulus was taken as 7.17e6 psi, with a Poisson's ratio of 0.323. Tensile yield stress was 6.3e4 psi.

Contact Surfaces
The concrete impact surface was modeled as a single layer of solid elements, and a contact

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surface was defined using the top surface of the concrete as the master surface and the lower fuselage grids as slave nodes. Early simulations showed that the wing was displacing through the keel beam, so a second contact surface was defined to allow the bottom of the wing to contact (and crush) the composite keel beam. The wing, keel beam and wing support structure is shown in Figure 13. This modification reduced unrealistic deformation in the rear fuselage.
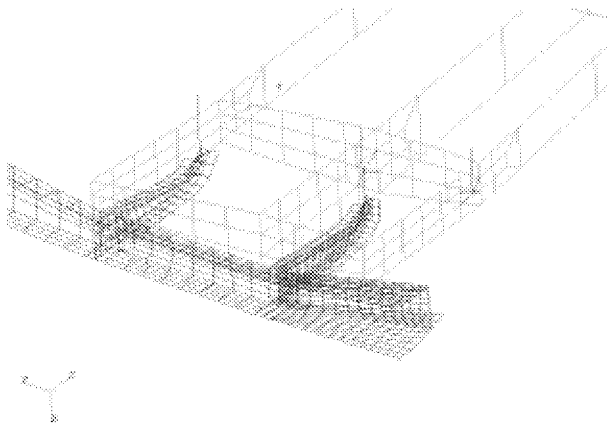

Figure 13. Keel Beam/Wing and attachment structural detail (skin not shown)

Simulation
Video and accelerometer test data showed that as expected, the acceleration pulses experienced by the passengers occurred over a time period of about 20 milliseconds, depending on seat location (see Figure 8). A period of 20 milliseconds, beginning with the initial contact, was therefore chosen as the minimum simulation time required to capture the significant structural responses.

Discussion

Due to the limited amount of instrumentation, the emphasis of the analytical effort was focused on simulating the structural damage that could be verified by recorded images. Attempts were also made to correlate some of the vertical

accelerations near the seat attachment points, since these accelerations are typically measured to estimate the dynamic inputs to the seats.
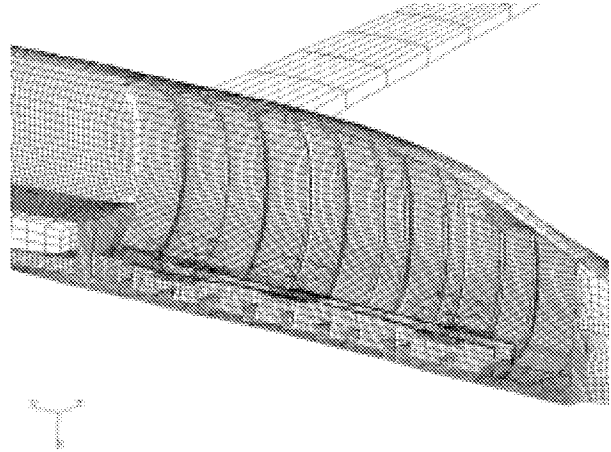
Figure 14. Deformed shape at time t = 0.010 sec

Airframe Structure Response
A deformed structure plot corresponding to t=0.010 seconds is shown in Figure 14. Note that the deformations are plotted to true scale. Several elements have failed by this time, including frame elements near the airplane centerline. This corresponds to the failure seen in the interior photograph of Figure 7. A detail

Figure 15. Failed elements simulating fuselage damage at time t = 0.010 (wing not shown)

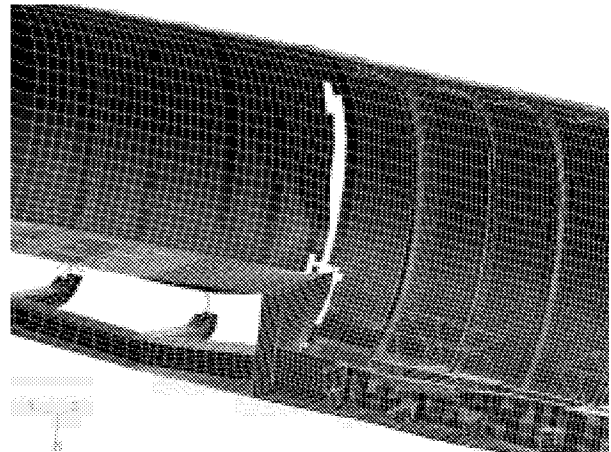of the fuselage near the wing, Figure 15, shows the circumferential fuselage damage that initiated at the forward wing attachment location. This damage matches closely the circumferential fuselage "unzipping" seen in the video (see also Figure 5). The crack at the aft wing attachment location does not appear in the simulation, probably because the wing has not yet hit the concrete impact surface.

Floor Beam/Seat Response
Early simulations generated excessive crushing of the composite subfloor beams. This behavior did not match the test results. A closer examination of the video footage from the interior cameras revealed that the seats, especially the energy-absorbing seats, deformed significantly on initial impact. This feature was not accounted for in the simulation, because the seats had been modeled only as very stiff beams, with a lumped mass element to represent the combined seat and passenger mass. In order to assess the effects of seat deformation, a finite element model was created of an energy-absorbing seat. This approximate seat model was integrated into the Lear Fan model, and a new simulation was performed. The differences show clearly that the seat flexibility has a significant effect on the response of the subfloor. Figure 16 shows a plot of vertical acceleration versus time near the inboard rear attachment point of Seat 1.
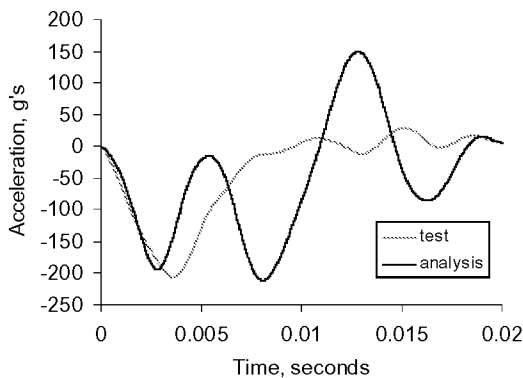

Figure 16. Vertical acceleration, Seat 1, near rear inboard attachment point.

The simulation predicted an initial peak acceleration of about 193 g's, compared with the experimental value of 206 g's. The second pulse in the analysis is a result of the approximate seat modeling. A more accurate seat model would be required to improve the correlation.

Conclusions

A finite element model of the Lear Fan aircraft was generated for use with the MSC.Dytran explicit dynamics code to simulate an impact test conducted at the NASA Langley IDRF. The modeling process for the Lear Fan fuselage was slow and cumbersome, due to the lack of detailed information. Future models could be created more efficiently by using a Computer Aided Design (CAD) or other surfacing tool to generate surfaces. Then the surfaces could be imported into MSC.Patran for generation of the FEM. Some aspects of the modeling process were also more difficult due to lack of support for certain features in MSC.Dytran preference of MSC.Patran. These features include modeling of PCOMPs, and support for the use of fields to compute initial velocity components.

The simulation captured key structural responses, such as the fuselage cracking at the forward wing attachment location, and the failure of the frames at the longitudinal centerline. It was found that simplified seat models were too stiff to accurately represent the interaction of the subfloors, seat rails, and passengers. Better results were obtained by improving the fidelity of the seat models.

Difficulties were encountered in test/analysis correlation, because the Lear Fan was instrumented for concept evaluation rather than for comparison with analysis. For example there was no synchronization of dynamic data, i.e. there was no way to correlate the timing of

the onboard data acquisition system with the video data, and it was difficult to identify the exact moment of initial contact. A synchronization capability would greatly facilitate the job of properly sequencing important events, such as initial impact, peak passenger accelerations, and structural failures. For example, it would have been relatively easy to determine whether the major fuselage failures occurred before, after, or during the time period in which the passengers experienced the peak loads. Also, while the second (head-on) impact allowed multiple test objectives to be accomplished, it also caused significant structural damage. In some cases it was not possible to determine whether damage was caused by the first or the second impact, and this made the correlation effort more difficult as well.

Acknowledgments

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